Utilization of Max-Min User Relay in Cooperative NOMA Systems

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Abstract— **Non-orthogonal multiple access (NOMA) has been focused to increase system capacity and spectral efficiency for the fifth generation (5G) mobile networks. In order to improve the performance of the NOMA systems with successive interference cancellation (SIC), a max-min user relay assisted cooperative NOMA scheme is investigated in this paper. The derived closed-form expression for outage probability is verified through Monte Carlo simulation results. We found that the performance with max-min relay outperforms the random relay. It is also shown that the performance of the destination user (DU) improves with the power allocation coefficient of DU. However, we noticed that there is an optimal value to minimize the outage probability of the relay-user (RU).**

Index Terms—**Non-Orthogonal Multiple Access (NOMA); Cooperative NOMA; User Relaying; 5G Cellular Networks.**

I. INTRODUCTION

Recently, non-orthogonal multiple access (NOMA) system, which transmit multiple user messages simultaneously in same frequency with different power levels, is considered as one of the candidate for multiple access in 5G cellular networks [1-5]. Though NOMA system increases the capacity and throughput compared to conventional orthogonal multiple access (OMA), an improvement can be attained by a cooperative transmission. In [6-7], a cooperative transmission have studied and obtained the performance improvements in NOMA system with successive interference cancellation (SIC).

Generally, the received signals both from the indirect and direct path are combined at a destination in a cooperative transmission, hence the severe channel impairment can be mitigated through the use of space diversity. For the construction of an indirect path, a relaying is introduced for delivering a source information to a destination. There are two kinds of relaying for NOMA cooperative transmission: the dedicated relaying and the user relaying.

Firstly, the dedicated relaying adapts standalone relay which is not selected among users. In [8], the outage probability of a paired user is derived using a dedicated relay in a cooperative NOMA system. And in [9], although it is not a cooperative system, a dedicated relay is employed. And the authors proposed the two-stage relay selection scheme based on the conventional max-min relay selection scheme, and derived the outage probability of the scheme [9]. However, in the case of a temporary network, i.e., an Ad-Hoc network, the dedicated relay is difficult to install permanently and increases system complexity.

Secondly, the user relaying select relays among users in NOMA system. One of the notable features of NOMA system with SIC, the users with better channel conditions can decode the messages for the others. Therefore the users can be used as relays to enhance the transmit reliability for the users with poor channel conditions [6]. Consequently, the user relaying does not necessary an extra dedicated relay. However, when all the users in NOMA system are participating in the relaying process, the signal processing grows heavily for SIC. To avoid this phenomenon, separate all users in NOMA system into user pairs (near user-far user pairs), and designates near user as a relay for the far user [5, 7, 10-11]. As we can see from the name, the near user and the far user, the criteria are based on the distances from a base station. Even the average received SNR is identical on equal distances, the instantaneous SNR is changing in fading channel. It is generally accepted that the relay selection based on the instantaneous channel gain has much performance gain than that based on the average SNR in fading channel.

Therefore in this paper, we consider a cooperative NOMA system with user relaying which utilize a selected relay-user (RU). For the relay selection, we applied max-min selection scheme to indirect paths [12-14]. We derive closed-form expressions for the outage probability of RU and a destination user (DU). Monte Carlo simulation performed. And the simulation results are coincident with the derived theoretical analysis, which verified our analysis.

On the other hand, the power allocation to RU and DU in a cooperative NOMA system with SIC affect the performance. It is noticed that the performance of DU improves with the power allocation coefficient to DU. However, there is an optimal value to minimize the outage probability of RU.

The remainder of this paper is organized as follows. In Section II, we present a cooperative NOMA system model and the transmission protocol. In Section III, analytical expressions are derived for the outage probability of RU and DU when the max-min relay selection is applied. Numerical examples are presented and verified through simulation in Section IV. Finally, concluding remarks are given in Section V.

II. SYSTEM MODEL

Consider a cellular down link scenario which have a base station S, K candidate relays R_i $(i = 1, 2, ..., K)$ and a destination user (DU) D as shown in Figure 1. According to the NOMA protocol, the base station S transmits the message to the selected RU R^* and DU in timeslot 1. RU is selected among K candidate relays, and will be mentioned in the following paragraph. And in timeslot 2, RU decodes its own information by applying SIC to the received signal from S and transmits the information for DU. We use the conventional decode-and-forward relay scheme. The received signal both from the RU and S is combined at DU with selection combining which selects the strongest signal.

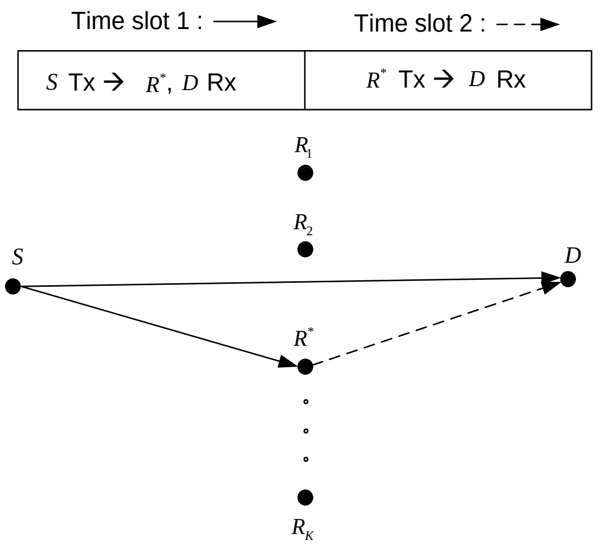

Figure 1: Cooperative NOMA transmission system

Prior to the source transmission, the best relay is selected to perform RU, where the max-min selection criterion is applied. The index of the selected relay of RU can be written by Equation (1).

$$k = \arg \underset{i=1,\ldots,K}{Max} \min\{\left|h_{SR_i}\right|^2,\ \left|h_{R_iD}\right|^2\} \tag{1}$$

where:

$\left|h_{SR_i}\right|^2$: Channel gain of $S - R_i$ path

$\left|h_{R_iD}\right|^2$: Channel gain of $R_i - D$ path

Denote the selected relay R_k as R^* for distinction. The base station S sends message to RU and DU based on the NOMA protocol, which is written by Equation (2).

$$s(n) = \sqrt{P_S}\left(a_D x_D(n) + a_R x_R(n)\right) \tag{2}$$

where:

P_S : Transmit power of S

a_D : Power allocation coefficient for DU

a_R : Power allocation coefficient for RU

x_D : Bipolar message symbol for DU

x_R : Bipolar message symbol for RU

In Equation (2), $a_D > a_R$ with $a_D^2 + a_R^2 = 1$ while $|x_D|^2 = |x_R|^2 = 1$. We assume the independent frequency non-selective Rayleigh block fading channels and the conventional decode-and-forward relaying for NOMA downlink cooperative system.

A. Received Signal at RU in Timeslot 1

The received signal at RU from S- path can be written by Equation (3).

$$y_{SR^*}(n) = \sqrt{P_{R^*}}\left(a_D x_D(n) + a_R x_R(n)\right) h_{SR^*} + n_{R^*}(n) \tag{3}$$

where:

P_{R^*} : Power received at RU

h_{SR^*} : Channel coefficient of $S - R^*$ path, which is Rayleigh distributed with unit variance

$n_{R^*}(n)$: Additive Gaussian noise with variance N_0

The received instantaneous signal-to-interference plus noise ratio (SINR) at the RU to detect $x_D(n)$ can be written by Equation (4).

$$\gamma_{SR^*}^{x_D} = \frac{P_{R^*} a_D^2 \left|h_{SR^*}\right|^2}{P_{R^*} a_R^2 \left|h_{SR^*}\right|^2 + N_0} = \frac{a_D^2 \left|h_{SR^*}\right|^2}{a_R^2 \left|h_{SR^*}\right|^2 + \frac{1}{\rho_{R^*}}} \tag{4}$$

where:

ρ_{R^*} : Received average signal–to-noise ratio (SNR) from $S - R^*$ path, with $\rho_{R^*} = P_{R^*} / N_0$

At RU, after decoding the $x_D(n)$, this component is subtracted from the received signal by SIC of NOMA. Thus the received instantaneous SNR at the RU to detect $x_R(n)$ can be written by Equation (5).

$$\gamma_{SR^*}^{x_R} = \frac{P_{R^*} a_R^2 \left|h_{SR^*}\right|^2}{N_0} = \rho_{R^*} a_R^2 \left|h_{SR^*}\right|^2 \tag{5}$$

B. Received Signal at DU in Timeslot 2

The received signal at DU from $R^* - D$ path can be written by Equation (6).

$$y_{R^*D}(n) = \sqrt{P_{R^*D}}\, h_{R^*D} a_D x_D + n_D(n) \tag{6}$$

where:

P_{R^*D} : Power received at DU from $R^* - D$ path.

The received SNR is given by Equation (7).

$$\gamma_{R^*D}^{x_D} = \frac{P_{R^*D} a_D^2 \left|h_{R^*D}\right|^2}{N_0} = \rho_{R^*D} a_D^2 \left|h_{R^*D}\right|^2 \tag{7}$$

where:

ρ_{R^*D} : Received average SNR from $R^* - D$ path; with $\rho_{R^*D} = P_{R^*D} / N_0$.

While the received signal from $S - D$ path at DU can be written by Equation (8).

$$y_{SD}(n) = \sqrt{P_{SD}}\left(a_D x_D(n) + a_R x_R(n)\right) h_{SD} + n_D(n) \tag{8}$$

And received SNR can be given by Equation (9).

$$\gamma_{SD}^{x_D} = \frac{P_{SD} a_D^2 \left|h_{SD}\right|^2}{P_{SD} a_R^2 \left|h_{SD}\right|^2 + N_0} = \frac{a_D^2 \left|h_{SD}\right|^2}{a_R^2 \left|h_{SD}\right|^2 + \dfrac{1}{\rho_{SD}}} \tag{9}$$

where:

ρ_{SD} : Received average from $S-D$ path; with $\rho_{SD} = P_{SD} / N_0$

The received signals from both the indirect path ($R^* - D$ path) and the direct path ($S - D$ path) are combined by SC at DU.

III. PERFORMANCE ANALYSIS

In the NOMA protocol, a base station transmit different messages to RU and DU simultaneously, hence the outage probability of RU and DU have to be derived separately.

A. Outage Probability of RU

An outage of RU occur for two cases. The first is that RU cannot detect *$x_D(n)$* . The second is that RU can detect *$x_D(n)$* but cannot detect *$x_R(n)$*. Under these two cases, the outage probability of RU can be expressed as Equation (10).

$$P_{o,R^*} = \Pr\left(\gamma_{SR^*}^{x_D} < \Gamma_1\right) + \Pr\left(\gamma_{SR^*}^{x_D} \ge \Gamma_1,\ \gamma_{SR^*}^{x_R} < \Gamma_2\right) \tag{10}$$

where:

Γ_1 : $2^{2R_D} - 1$

Γ_2 : $2^{R_R} - 1$

R_D : Transmission capacity of DU

R_R : Transmission capacity of RD

Substituting Equation (4) into the first probability term of Equation (10), will give Equation (11) as follows.

$$\Pr\left(\gamma_{SR^*}^{x_D} < \Gamma_1\right) = \Pr\left(\left|h_{SR^*}\right|^2 < \frac{\Gamma_1}{\rho_{R^*}(a_D^2 - \Gamma_1 a_R^2)}\right) = \Pr\left(\left|h_{SR^*}\right|^2 < \xi\right) \tag{11}$$

where:

ξ : {eq} $\xi = \Gamma_1 / \rho_{R^*}(a_D^2 - \Gamma_1 a_R^2)$

And to guarantee that $\left|h_{SR^*}\right|^2 > 0$, $\Gamma_1 < a_D^2 / a_R^2$ must be satisfied. Substituting Equation (5) into the probability of $\Pr\left(\gamma_{SR^*}^{x_R} < \Gamma_2\right)$ in the second probability of Equation (10), will give Equation (12) as follows.

$$\Pr\left(\gamma_{SR^*}^{x_R} < \Gamma_2\right) = \Pr\left(\left|h_{SR^*}\right|^2 < \frac{\Gamma_2}{\rho_{R^*} a_R^2}\right) = \Pr\left(\left|h_{SR^*}\right|^2 < \eta\right) \tag{12}$$

where:

η : $\frac{\Gamma_2}{\rho_{R^*} a^2{}_R}$

Replacing Equations (11) and (12) into Equation (10), we obtain Equation (13) as follows:

$$P_{o,R^*} = \Pr\left(\left|h_{SR^*}\right|^2 < \xi\right) + \Pr\left(\left|h_{SR^*}\right|^2 \ge \xi,\ \left|h_{SR^*}\right|^2 < \eta\right) \tag{13}$$

which is equal to Equation (14).

$$P_{o,R^*} = \begin{cases} \Pr\left(\left|h_{SR^*}\right|^2 < \eta\right), & \eta \ge \xi \\ \Pr\left(\left|h_{SR^*}\right|^2 < \xi\right), & \eta < \xi \end{cases} \tag{14}$$

Consequently, Equation (14) can be expressed by Equation (15).

$$P_{o,R^*} = F_{\left|h_{SR^*}\right|^2}\left\{\max(\eta, \xi)\right\} \tag{15}$$

where:

$F_{\left|h_{SR^*}\right|^2}\{x\}$: Cumulative distribution function (CDF) of $\left|h_{SR^*}\right|^2$.

We can obtain the CDF by taking the integration of the probability density function (PDF) of $\left|h_{SR^*}\right|^2$. Therefore let's derive the PDF first.

For the notational brevity, we denote $\left|h_{SR^*}\right|^2 = H_{R^*}$, $\left|h_{R^*D}\right|^2 = G_{R^*}$, $\left|h_{SR_i}\right|^2 = H_i$, and $\left|h_{R_iD}\right|^2 = G_i$. The PDF of H_{R^*} can be written by Equation (16).

$$p_{H_{R^*}}(x) = \int_0^\infty p_{H_i|Z_i=z}(x|z)\, p_{\max(Z_i)}(z)\, dz \tag{16}$$

where:

Z_i : *$\min(H_i, G_i)$*

Assuming each channel is independent, the CDF of Z_i is given by Equation (17).

$$\begin{aligned} F_{Z_i}(z) &= 1 - \Pr\left(H_i \ge z\right)\Pr\left(G_i \ge z\right) \\ &= 1 - e^{-2z} \end{aligned} \tag{17}$$

The conditional PDF in Equation (16) can be written by:

$$p_{H_i|Z_i=z}(x|z) = \frac{p_{H_i, Z_i=z}(x,z)}{p_{Z_i}(z)} \tag{18}$$

Because of the joint CDF $F_{H_i, Z_i=z}(x,z)$ is discontinuous, the joint PDF $p_{H_i, Z_i=z}(x,z)$ in Equation (18), which is the derivative of the joint CDF, includes an impulse term at $x = z$ [15]. Therefore the conditional PDF can be written by Equation (19).

$$p_{H_i|Z_i=z}(x|z) = \frac{p_{H_i}(x)\, p_{G_i}(z)}{p_{Z_i}(z)} + \frac{p_{H_i}(z)\left\{1 - F_{G_i}(z)\right\}}{p_{Z_i}(z)}\delta(x - z) \tag{19}$$

By taking derivative to Equation (17), we obtain Equation (20) as follows.

$$p_{Z_i}(z) = 2e^{-2z} \tag{20}$$

Replacing $p_{H_i}(x) = e^{-x}$, $p_{G_i}(z) = e^{-z}$, and $F_{G_i}(x) = 1 - e^{-x}$ into Equation (19), the conditional PDF is given by Equation (21).

$$p_{H_i|Z_i=z}(x|z) = \frac{1}{2}e^{-x+z} + \frac{1}{2}\delta(x-z) \tag{21}$$

The PDF of $p_{\max(Z_i)}(z)$ in Equation(16) can be rearranged to obtain Equation (22).

$$\begin{aligned} p_{\max(Z_i)}(z) &= \frac{\partial F_{\max(Z_i)}(z)}{\partial z} = \frac{\partial}{\partial z}\prod_{i=1}^{N} F_{z_i}(z) \\ &= 2Ne^{-2z}\left(1-e^{-2z}\right)^{N-1} \\ &= \sum_{i=1}^{N}\binom{N}{i}(-1)^{i-1}2ie^{-2iz} \end{aligned} \tag{22}$$

Substituting Equations (19) and (22) into Equation (16), the PDF of H_{R^*} is given by Equation (23).

$$p_{H_{R^*}}(x) = \sum_{i=1}^{N}\binom{N}{i}(-1)^{i-1}\frac{i}{1-2i}\left(e^{-2ix} - e^{-x}\right) + \sum_{i=1}^{N}\binom{N}{i}(-1)^{i-1}ie^{-2ix} \tag{23}$$

By taking integral to Equation (23), the CDF can be written by Equation (24).

$$\begin{aligned} F_{H_{R^*}}(x) = &\sum_{i=1}^{N}\binom{N}{i}(-1)^{i-1}\frac{i}{1-2i}\left\{\frac{1}{2i}\left(1-e^{-2xi}\right) - \left(1-e^{-x}\right)\right\} \\ &+ \frac{1}{2}\sum_{i=1}^{N}\binom{N}{i}(-1)^{i-1}\left(1-e^{-2xi}\right) \end{aligned} \tag{24}$$

Consequently, the outage probability of RU in Equation (15) can be obtained from Equation (24).

$$P_{o,R^*} = F_{H_{R^*}}\left\{\max\left(\varsigma,\ \eta\right)\right\} \tag{25}$$

B. Outage Probability of RU

From the system model description in section 2, the received signals both from the indirect path ($R^* - D$ path) and direct path ($S - D$ path) are combined at DU with SC. Therefore, the outage probability of DU can be obtained by multiplying the outage probability of the indirect path and that of the direct path, and can be expressed as Equation (26).

$$P_{o,D} = P_{o,ind}P_{0,dir} \tag{26}$$

where:

$P_{o,ind}$: Outage probability of the indirect path

$P_{0,dir}$: Outage probability of the direct path

The indirect path are composed of $S - R^*$ path and $R^* - D$ path. When any component of the indirect path fails, the outage happens. The outage probability of the indirect path can be written by Equation (27).

$$\begin{aligned} P_{o,ind} &= \Pr\left\{\min(\gamma_{SR^*}^{x_D}, \gamma_{R^*D}^{x_D}) < \Gamma_1\right\} \\ &= \prod_{i=1}^{K} \Pr\left\{\min(\gamma_{SR_i}^{x_D}, \gamma_{R_iD}^{x_D}) < \Gamma_1\right\} \\ &= \prod_{i=1}^{K} \left\{1 - \Pr\left(\gamma_{SR_i}^{x_D} \geq \Gamma_1\right)\Pr\left(\gamma_{R_iD}^{x_D} \geq \Gamma_1\right)\right\} \end{aligned} \tag{27}$$

By replacing R_i instead of R^* in Equation (11), the probability of $\Pr\left(\gamma_{SR_i}^{x_D} < \Gamma_1\right)$ can be written by Equation (28).

$$\Pr\left(\gamma_{SR_i}^{x_D} < \Gamma_1\right) = \Pr\left(\left|h_{SR_i}\right|^2 < \frac{\Gamma_1}{\rho_{R_i}(a_D^2 - \Gamma_1 a_R^2)}\right) = \Pr\left(\left|h_{SR_i}\right|^2 < \xi_i\right) \tag{28}$$

where:

ρ_{R_i} : $\frac{P_{R_i}}{N_0}$

ξ_i : $\frac{\Gamma_1}{\rho_{R_i}(a^2{}_D - \Gamma_1 a^2{}_R)}$

Similarly, the probability of $\Pr\left(\gamma_{R_iD}^{x_D} < \Gamma_1\right)$ can be obtained from Equation (7), and is given by Equation (29).

$$\Pr\left(\gamma_{R_iD}^{x_D} < \Gamma_1\right) = \Pr\left(\left|h_{R_iD}\right|^2 < \frac{\Gamma_1}{\rho_{R_iD}a_D^2}\right) = \Pr\left(\left|h_{R_iD}\right|^2 < \lambda_i\right) \tag{29}$$

where:

ρ_{R_iD} : $\frac{P_{R_iD}}{N_0}$

λ_i : $\frac{\Gamma_1}{\rho_{R_iD}a^2{}_D}$

Substituting Equations (28) and (29) into Equation (27), the outage probability of the indirect path can be written by Equation (30).

$$P_{o,ind} = \prod_{i=1}^{K}\left\{1 - e^{-(\lambda_i + \xi_i)}\right\} \tag{30}$$

Also with Equation (9), the outage probability of the direct path can be written by Equation (31).

$$P_{0,dir} = \Pr\left(\gamma_{SD}^{x_D} < \Gamma_1\right) = \Pr\left(\left|h_{SD}\right|^2 < \chi\right) = 1 - e^{-\chi} \tag{31}$$

where:

χ : $\frac{\Gamma_1}{\rho_{SD}(a^2{}_D - a^2{}_R\Gamma_1)}$

Combining Equations (30) and (31), the outage probability of DU of Equation (26) can be obtained by Equation (32).

$$P_{o,D} = \prod_{i=1}^{K}\left\{1 - e^{-(\lambda_i + \xi_i)}\right\}(1 - e^{-\chi}) \tag{32}$$

IV. NUMERICAL STUDIES

Figure 2 depicts the outage probability of RU versus average SNR with different power coefficient. To focus on the performance gain of the max-min selection scheme, we assumed the received average SNR of each relay and destination on the indirect path is identical. Monte Carlo simulations are performed to validate the derived results. We noticed that excellent agreement between the analytic and simulation results.

In addition, we compared the performance of the max-min selection and random selection: “Max-min” denotes the max-min relay selection and “Random” denotes random selection in Figure 2. We noticed that the performance with max-min selection is much better than with random selection.

It is generally accepted that the decrease of the received power degrades the performance of the receiver. For this reason, we can suppose that the decrease of the power allocation coefficient for RU, a_R^2, consequently increases the outage probability of RU. Notice that $a_D^2 + a_R^2 = 1$, that is a decrease of a_R^2 means an increase of a_D^2. Therefore, we can expect that an increase of a_D^2 degrades of the outage probability of RU. However, Figure 2 shows the outage probability of RU does not degrade with a_D^2. Since in NOMA system, the outage probability of RU is not only a function of a_R^2 but also of a_D^2 with $a_D^2 + a_R^2 = 1$ as shown in Equation (25).

Comparing the outage probability of a_D^2 equals 0.9 to that of 0.8 in Figure 2, we expect the outage probability with a_D^2 = 0.9 is worse than that with a_D^2= 0.8. To the contrary, the outage probability with a_D^2 = 0.9 is better than that with a_D^2 = 0.8. The reason is η is greater than ς under a certain condition in Equation (25). Therefore we can expect there is an optimum values of a_D^2.

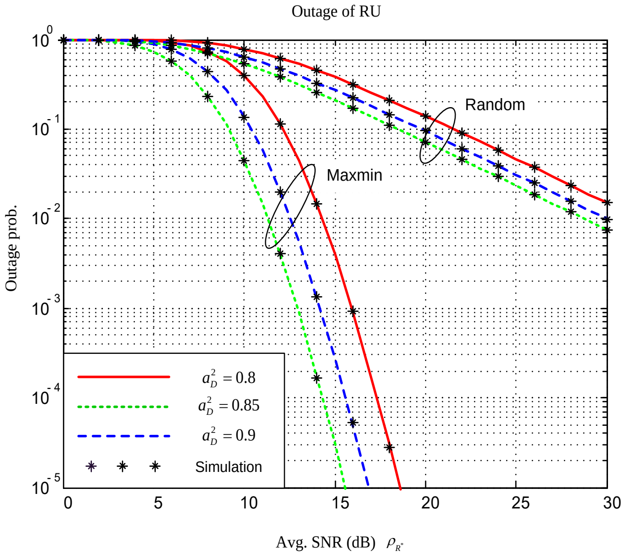

Figure 2: Outage probability of RU with different power allocations (R_D = R_R = 1, K = 10, $\rho_{R^*} = \rho_{R_i} = \rho_{R^*D} = \rho_{R_iD}$)

The outage probability of RU versus power allocation coefficient a_D^2 with different SNR is shown in Figure 3. This figure denotes the optimum value of a_D^2 is approximately 0.86 under the given condition, $R_D = R_R = 1,\ K = 10$. It is noticed that the outage probability is the more susceptible with the more SNR. Consequently, the optimum power allocation to RU and to DU is important to maintain the minimum outage probability.

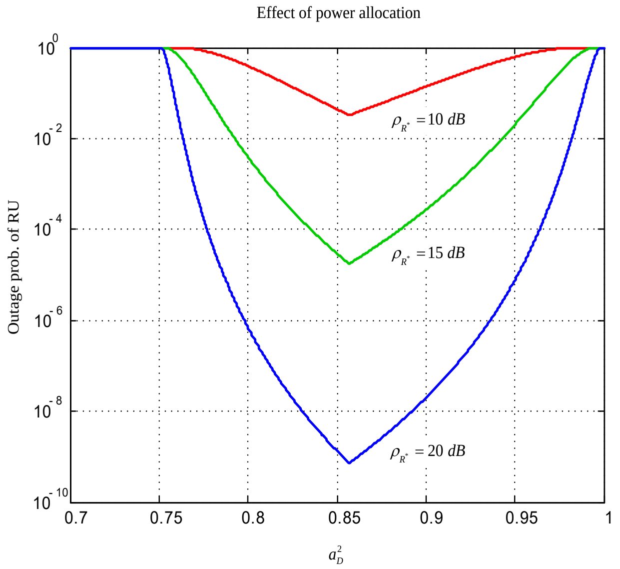

Figure 3: Outage probability of RU versus power allocation coefficient (R_D = R_R = 1, K = 10, $\rho_{R^*} = \rho_{R_i} = \rho_{R^*D} = \rho_{R_iD}$)

The outage probability of DU which combine signals both from the direct and indirect paths with SC is shown in Figure 4. Also, we assumed the received average SNR of each relay and destination on the indirect path is identical as in Figure 2. But in the cellular system, the distances to DU is generally far from BS compared to RU. Thus we assumed DU receives 0.2 times of average SNR of the indirect path. It is observed that the outage probability of DU is decreased with a_D^2. It is interpreted that the increase of a_D^2 means more transmission power to DU, hence decreases the outage probability.

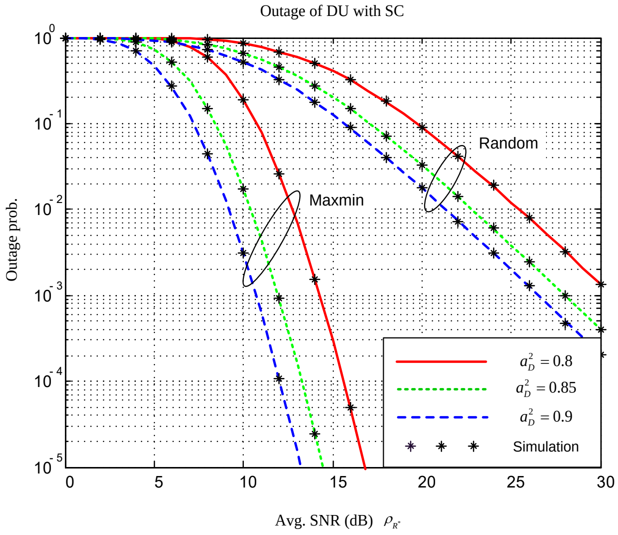

Figure 4: Outage probability of DU with different power allocations (R_D = R_R = 1, K = 10, $\rho_{R^*} = \rho_{R_i} = \rho_{R^*D} = \rho_{R_iD}, \rho_{SD} = 0.2\rho_{R^*D}$)

V. CONCLUSION

In this paper, we consider a cooperative NOMA system with SIC in 5G cellular networks. For cooperation, we adapt user relaying scheme with the max-min relay selection criteria. We derive analytical expressions of outage probability of RU and DU in closed-form, and verified through Monte Carlo simulation. It shows that the analytical and simulation results are exactly matched. Also we noticed that the performance with max-min relay selection outperforms that with random relay selection.

In regards to the power allocation in NOMA system with SIC, the performance of DU improves with the power allocation coefficient a_D^2. However, there is an optimal value to minimize the outage probability of RU. Therefore the analytical derivation for optimal power allocation between users should be investigated. This issue is left for future study.

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